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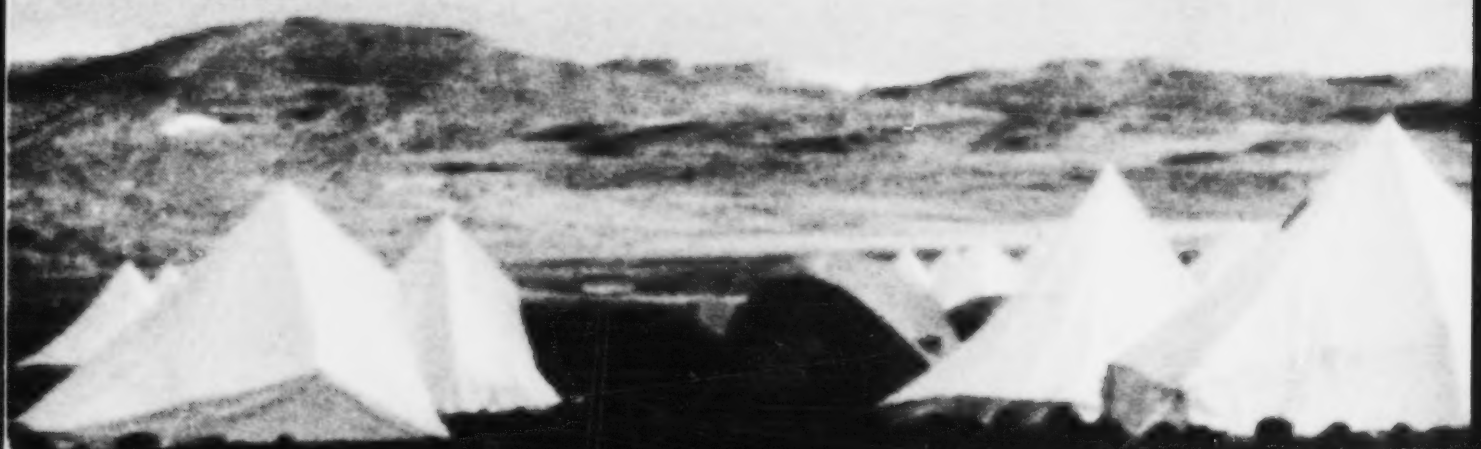

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Using downhole geophysical logs to provide detailed lithology and stratigraphic assignment, Oak Ridges Moraine, southern Ontario

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Abstract: In a regional hydrogeology study, Oak Ridges Moraine area, southern Ontario, downhole geophysical logs from 11 deep (about 90–190 m), plastic-cased, continuously logged boreholes helped establish these sites as high-quality stratigraphic benchmarks. Acquired logs include natural gamma, conductivity, magnetic susceptibility, spectral gamma, temperature, and seismic velocity measurements. The downhole logs provide detailed physical properties (at submetre to metre scale) that aid in lithological characterization and in determining subsurface stratigraphy. While natural gamma, conductivity, and magnetic susceptibility logs are useful to identify varied lithological units downhole, they cannot be used alone to differentiate the Newmarket Till (a regionally significant aquitard) from overlying or underlying units. However, this till is characterized by seismic velocities (>2500 m/s) that are significantly higher than most other sediments encountered in these boreholes. Seismic velocities also show promise as a porosity indicator and spectral gamma logs provide relative density estimates.

Résumé : Dans le cadre d'une étude hydrogéologique régionale dans la région de la Moraine d'Oak Ridges, dans le sud de l'Ontario, des diagraphies géophysiques continues recueillies dans 11 sondages profonds (de 90 à 190 m de profondeur environ) tubés en plastique révèlent que ces sites constituent d'excellents repères stratigraphiques. Les diagraphies obtenues comprennent des mesures de rayons gamma naturels, de la conductivité, de la susceptibilité magnétique, de la température et des vitesses sismiques, ainsi que des diagraphies spectrales de rayons gamma. Elles fournissent des renseignements détaillés sur les propriétés physiques des roches à l'échelle submétrique à métrique, ce qui facilite la caractérisation de la lithologie et la détermination de la stratigraphie subsuperficielle. Bien que les diagraphies de rayons gamma naturels, de la conductivité et de la susceptibilité magnétique soient utiles pour reconnaître les diverses unités lithologiques dans les sondages, elles ne permettent pas, à elles seules, de différencier le Till de Newmarket (un important aquitard de la région) des unités sus-jacentes et sous-jacentes. Cependant, ce till se distingue par des vitesses sismiques significativement plus élevées (> 2500 m/s) que dans la plupart des autres sédiments dans ces sondages. Les vitesses sismiques constitueraient également un moyen prometteur de déterminer la porosité des sédiments, et les diagraphies spectrales de rayons gamma fournissent des estimations de la densité.

INTRODUCTION

The Oak Ridges Moraine is a prominent sandy ridge north of Lake Ontario (Fig. 1). Along with underlying sediments, it forms a thick (up to 200 m), extensive Quaternary aquifer complex that supplies groundwater to more than 200 000 people within the Greater Toronto Area, as well as to much of the rural population in the region. Increasing pressures of rapid urbanization (e.g. Gore and Storrie Ltd. and MacViro Consultants Inc., unpub. rept., 1993; Oak Ridges Moraine Conservation Act, 2001) have led to questions relating to the long-term sustainability of this groundwater resource. A better understanding of the regional geological setting, architecture, and depositional environment of the complex glacial deposits in the area is required to improve evaluations of regional groundwater resources and flow, and to allow more cost-effective searches for additional groundwater supplies. A particular role for geophysical methods has been to provide laterally and vertically continuous data for delineating the significant geological and hydrogeological units across the area (e.g. Sibul et al., 1977; Fligg and Rodriques, 1983; Eyles et al., 1985; Boyce et al., 1995).

The Oak Ridges Moraine area has been the focus of a multidisciplinary hydrogeological study initiated in 1993 (e.g. Sharpe et al., 1996; Hinton et al., 1998; Pugin et al., 1999). The overall purpose of the work has been 1) to map surface and subsurface geology for regional groundwater assessments and 2) to develop methods to characterize the geological and hydrogeological settings within the Oak Ridges Moraine area. Both surface (e.g. Pullan et al., 1994, 2001; Pugin et al., 1999) and borehole geophysical surveys (Pullan et al., 2000, 2001; Taylor et al., 1999) have played a prominent role in establishing a high-quality geological framework. This paper examines the contribution of downhole geophysical logging to lithological characterization and delineation of subsurface hydrostratigraphic units. The data discussed include a suite of logs (natural gamma, conductivity, magnetic susceptibility, relative density, temperature, and downhole seismic) that have not been looked at in combination in this area (e.g. M.M. Dillon, unpub. rept., 1994; Golder and Associates, unpub. rept., 1994; Fenco MacLaren Inc., unpub. rept., 1994).

GEOLOGICAL SETTING

The Oak Ridges Moraine is a sandy, glaciofluvial-glaciolacustrine landform complex deposited primarily by meltwater processes near the margin of the Laurentide Ice Sheet (Barnett et al., 1998). It extends approximately 160 km east from the Niagara Escarpment and reaches 20 km in width (Fig. 1); its crest is approximately 250 m above Lake Ontario (Fig. 2). The last major ice advance deposited a thick widespread till sheet (Newmarket Till), which appears to be continuous under the Oak Ridges Moraine (Gwyn and Cowan, 1978). Where this till sheet is exposed north of the Oak Ridges Moraine, it forms northeast-trending drumlins that are dissected by a network of channels (Barnett, 1995). The Oak Ridges Moraine rests on this eroded terrain or directly on underlying older sediments (Fig. 1, 2). The unconsolidated Pleistocene sequence (0–200 m thick) unconformably overlies Paleozoic shale and carbonate.

A conceptual geological model developed for the glacial deposits of the Oak Ridges Moraine area (Sharpe et al., 1996; Barnett et al., 1998) identifies the following four major units and two erosional surfaces (Fig. 2): Halton/Kettleby sediments (thin surficial aquifer and aquitard units); Oak Ridges

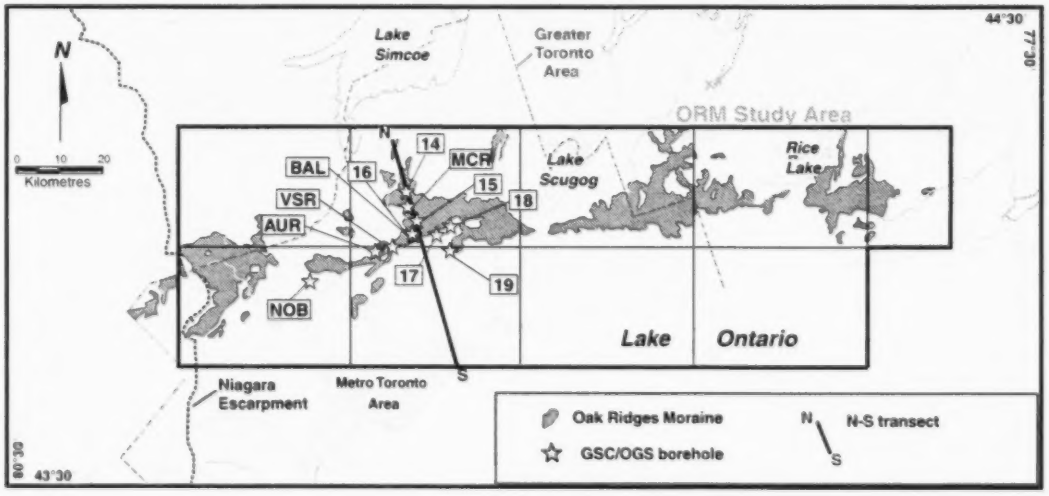

Figure 1. Map showing the Oak Ridges Moraine (ORM) area and borehole locations (OGS-PJB-14, OGS-PJB-15, OGS-PJB-16, OGS-PJB-17, OGS-PJB-18, and OGS-PJB-19, and GSC-BH-NOB, GSC-BH-AUR, GSC-BH-VSR, GSC-BH-MSR, and GSC-BH-BAL).

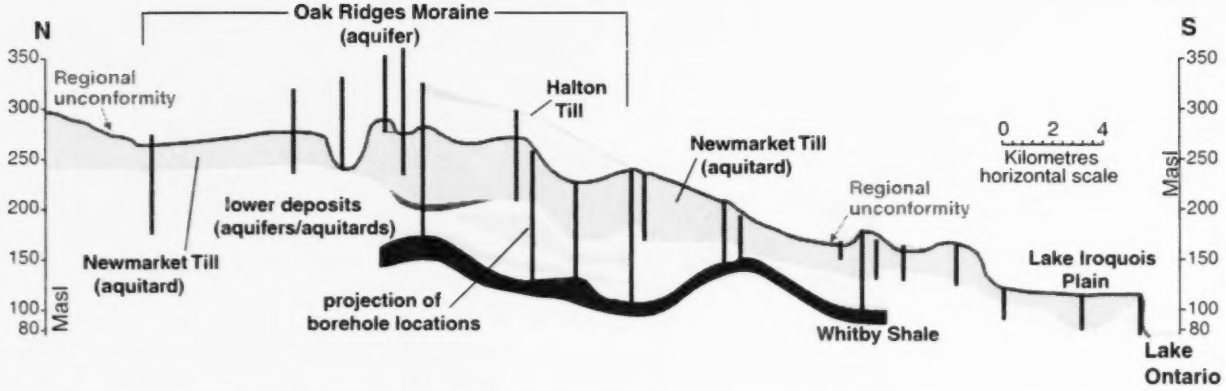

Figure 2. *North-south schematic cross-section from south of Lake Simcoe to Lake Ontario (see Fig. 1), based on high-quality borehole data, showing major elements of the geological/hydrostratigraphic model of the Oak Ridges Moraine area (*modified from *Sharpe et al., 1994). Masl = metres above sea level*

Moraine sediment (aquifer); channelized erosional surface on the Newmarket Till; Newmarket Till (aquitard); lower sediment (includes aquifer and aquitard units); and erosional bedrock surface.

The model emphasizes the extensive nature of the Newmarket Till and the importance of channels eroded into or through it beneath the Oak Ridges Moraine. The Newmarket Till is a regional aquitard that separates the largely unconfined Oak Ridges Moraine aquifer from underlying aquifers within the lower deposits. Although vertical leakage occurs through the till (Gerber and Howard, 2000), where the Newmarket Till is eroded, there is a potential for greater hydraulic connection between these aquifers (Desbarats et al., 2001; Sharpe et al., 2002). Furthermore, coarse-grained fill within these channels may be targets for high-yield water wells (e.g. Sharpe et al., 1996). Thus, the Newmarket Till plays a crucial role in the regional hydrostratigraphy.

DOWNHOLE GEOPHYSICAL LOGGING IN HYDROGEOLOGICAL INVESTIGATIONS

Downhole geophysical logs provide a remote means of characterizing and identifying lithological and stratigraphic units from variations in their physical properties. In this way, geophysical logs can be used to supplement geological assignment based on drill core logs (e.g. Morin, 2000); they provide detailed lithological and stratigraphic information from unsampled or wash-bored boreholes. The identification of geophysical 'markers' and trends in physical properties allows correlation between boreholes and with surface geophysical methods (Paillet, 1995).

Specific geophysical properties of unconsolidated materials, such as density, natural formation radiation, and electrical conductivity, can be utilized to identify and characterize aquifers and their confining units (e.g. Keys, 1989). Aquitards are commonly fine-grained units characterized by high natural gamma count rates and high electrical conductivity (i.e. low resistivity). In contrast, aquifers are often sand and gravel units that typically have low count rates and low conductivities. Some aquitard and aquifer units can be defined solely on the basis of their natural gamma and/or conductivity (resistivity) characteristics (e.g. International Water Supply, unpub. rept., 1988). In many cases this approach works well, although this paper demonstrates that this is not necessarily the case in the Oak Ridges Moraine area.

Methods

An extensive suite of downhole geophysical logs has been acquired in 11 deep, continuously cored boreholes drilled in the Oak Ridges Moraine area (Fig. 1) between 1993 and 1997 by the Ontario Geological Survey (OGS) (Barnett, 1993) and the Geological Survey of Canada (GSC). All stratigraphic boreholes were cased with PVC pipe (6–7.5 cm inner diameter) to preserve borehole access and permit downhole electrical and magnetic geophysical logging. Access to three OGS boreholes drilled in active gravel pits has since been lost.

The geophysical logs were acquired using three portable geophysical systems with 'slim hole' sondes (i.e. downhole tools that could be used in small-diameter boreholes): 1) Geonics EM-39 system with natural gamma, inductive conductivity, and magnetic susceptibility sondes; 2) IFG portable logging system with temperature and spectral gamma-gamma density sondes (using an uncollimated cobalt-60 source); and 3) downhole seismic systems (both compressional (P-wave) and shear (S-wave)), built in-house.

Table 1 lists the downhole geophysical logs acquired in the Oak Ridges Moraine study, the actual quantities measured and specific survey objectives, the radius of investigation, the scale of measurements, and the practical interpretation of each log.

Table 1. Details on the downhole geophysical logs acquired in continuously cored boreholes in the Oak Ridges Moraine study.

Downhole geophysical log [surveys completed]	Quantity measured [survey objectives]	Radius of investigation [scale of measurement]	Practical interpretations
Natural gamma [11 stratigraphic boreholes]	Number of gamma rays (produced by decay of K, U, Th) [lithology; borehole-to-borehole correlation of stratigraphic units]	0.3 m [submetre]	grain size (high counts associated with K in clay minerals)
Electrical conductivity [11 stratigraphic boreholes]	Quadrature component of magnetic field induced by alternating magnetic field in transmitter coil [lithology; borehole-to-borehole correlation of stratigraphic units]	2–3 m [submetre]	formation conductivity (grain and/or porewater conductivity)
Magnetic Susceptibility [11 stratigraphic boreholes]	In-phase component of above [lithology; borehole-to-borehole correlation of stratigraphic units]	1–1.5 m [submetre]	magnetite (heavy mineral) concentration (lithology)
Spectral gamma-gamma density [7 stratigraphic boreholes]	Number of gamma rays returned to probe due to Compton scattering [estimate density variations downhole]	0.3 m [submetre]	water table, bulk relative soil density
Spectral gamma-gamma ratio [7 stratigraphic boreholes]	Ratio of high-energy/low-energy gamma counts [estimate variations in bulk atomic number]	0.3 m [submetre]	variation in heavy mineral content, void ratio, or moisture content
Temperature [7 stratigraphic boreholes (this paper) 38 boreholes/water wells (Taylor et al., 1999)]	temperature (± 0.005°C) (temperature gradient = dT/dz) [indications of groundwater flow]	within borehole [submetre]	thermal history (equilibrium temperature), lithology (as related to thermal conductivity), anomalies due to groundwater flow
Seismic velocity [11 stratigraphic boreholes (P-wave) 1 stratigraphic borehole (S-wave)]	arrival times of seismic signal (compressional/shear) from surface (determination of P-wave/S-wave velocity) [lithology; velocity control for seismic reflection survey]	metres [metres]	variation in lithology, compaction, identification of reflecting horizons

The natural gamma, conductivity, magnetic susceptibility, temperature, and gamma-gamma logs were typically acquired at a logging speed of 2.5 cm/s. Further information on these logs may be found at http://sts.gsc.nrcan.gc.ca/clf/borehole_geophysic.asp or in Douma et al. (1999).

The seismic surveys were carried out using a downhole receiver array and a surface source close to the borehole. The first arrivals on the downhole seismic data are used to determine accurate interval velocities as a function of depth. In the case of compressional (P) waves, data were obtained using a multi-channel hydrophone array (12 or 24 hydrophones at 0.5 m spacing) in a water-filled borehole and a small impulsive surface source. Shear (S)-wave logs were obtained using a clamped, three-component downhole receiver and a loaded I-beam surface plate and hammer as a source. The downhole seismic systems and processing techniques are described in detail in Hunter et al. (1998).

RESULTS

Using geophysical logs to provide lithological information

Natural gamma and conductivity (or resistivity) logs are commonly used to provide estimates of lithology (e.g. M.M. Dillon, unpub. rept., 1994). For the boreholes discussed here, other geophysical logs are also available, including the magnetic susceptibility log that has proven to be an effective indicator of subsurface lithological and stratigraphic variations in unconsolidated sediments (McNeill et al., 1996).

Figure 3a shows the complete suite of logs obtained in the deepest and most westerly (Nobleton) stratigraphic borehole (GSC-BH-NOB; Fig. 1), where Oak Ridges Moraine sediments (0–60 m depth) lie above a complex sequence of lower deposits. No Newmarket Till was encountered in this hole.

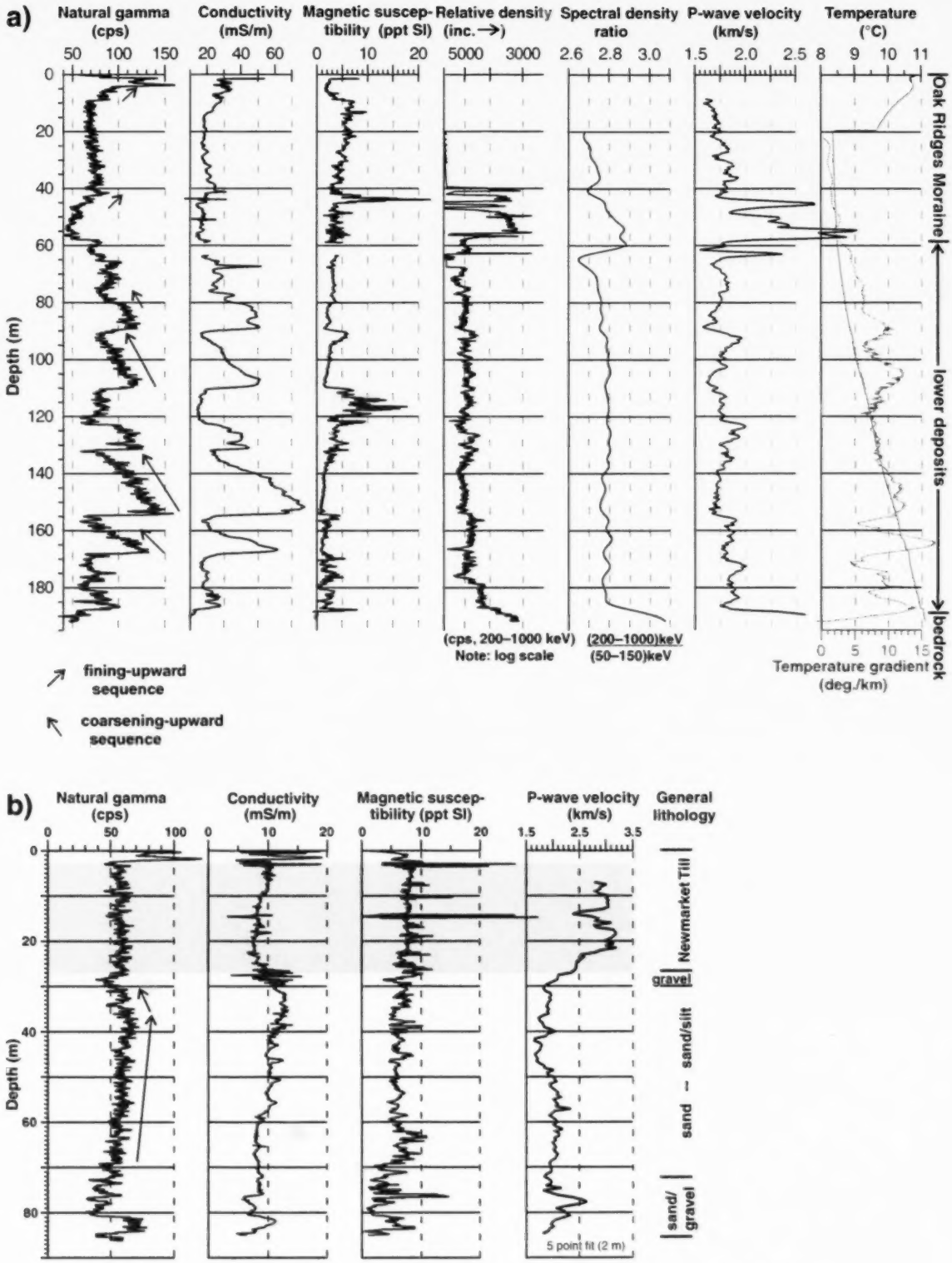

Figure 3. *Suite of geophysical logs for boreholes* ***a****) GSC-BH-NOB and* ***b****) OGS-PJB-14.*

The natural gamma, conductivity, and magnetic susceptibility logs clearly delineate the varied lithological units encountered in this borehole. The surficial sediment is a silty clay (0–4 m depth; 120 cps) capping a fining-upward silt sequence (5–10 m). The Oak Ridges Moraine package is predominantly sand (10–41 m; 65–80 cps), which the logs suggest coarsens upward slightly (decreasing gamma count, increasing magnetic susceptibility). A thick sequence of gravels at the base of the Oak Ridges Moraine deposits (45–60 m) is clearly delineated by low gamma counts. The fining-upward sequence at the top of the gravels is characterized by a magnetic susceptibility high. A complex sequence of lower deposits is characterized by a distinctive set of coarsening-upward units that can be correlated across much of the northwestern survey area (Fligg and Rodrigues, 1983). Coarse-grained units within the lower deposits are characterized by low gamma counts and conductivities, and commonly show slightly elevated magnetic susceptibilities. The fine sand unit at 110 to 120 m depth is clearly delineated by its high magnetic susceptibilities (high magnetite content).

Figure 3b shows the logs obtained in borehole OGS-PJB-14, which was drilled into Newmarket Till at the edge of a gravel pit in the north-central Oak Ridges Moraine (Fig. 1). Here little variation occurs in the natural gamma, conductivity, and magnetic susceptibility measurements downhole. These logs indicate that lithological units are coarse grained with slightly lower gamma counts at 28 to 30 m and 72 to 80 m depth correlating with gravel layers. However, these three logs alone do not suggest that two major stratigraphic units were encountered in this hole. The Newmarket Till (0–26 m depth) and the underlying sandy lower sediment can be differentiated only using the velocity log. A gradual fining-upward trend is noted in the lower sediment package, which contrasts with the coarsening-upward units in the Nobleton borehole (Fig. 3a).

High velocity, a distinguishing characteristic of Newmarket Till

Despite its hydrostratigraphic importance as a regional aquitard in the Oak Ridges Moraine, area, the Newmarket Till, where present, is difficult to differentiate from overlying Oak Ridges Moraine sediments or underlying lower sediment (Fig. 3b) solely on the basis of the geophysical logs that are usually used for stratigraphic correlation (i.e. gamma, conductivity/resistivity). In many cases (e.g. Fig 4a, b), even careful analysis of the natural gamma, conductivity, and magnetic susceptibility logs does not allow a clear and unambiguous identification of the three major stratigraphic units — Oak Ridges Moraine, Newmarket Till, and lower sediment. In other cases (Fig. 4c, d), subtle changes in gamma counts and/or conductivity at the Newmarket Till interface are observed.

In contrast, P-wave velocity logs (Fig. 3b, 4) clearly identify the Newmarket Till as a unit characterized by high seismic velocities (>2500 m/s). Both overlying and underlying sediments have significantly lower velocities, except for some gravel layers in which velocities surpass 2000 m/s (e.g. Fig. 3a) and basal till units in which velocities of 2000 to 3000 m/s have been observed. Detailed stratigraphic logging (Barnett, 1993; P.J. Barnett, pers. comm., 1995) indicates that slightly lower velocity layers within the till unit (e.g. Fig. 4a, c) correlate with zones in which the till is interlayered with finer grained sediments.

These data indicate that, within the Oak Ridges Moraine area, compressional wave velocity is actually a more diagnostic indicator of the Newmarket Till than several other geophysical logs. The velocity logs from a north-south borehole transect across the Oak Ridges Moraine (Fig. 5) show that the Newmarket Till (as indicated by velocities greater than 2500 m/s) can be traced over tens of kilometres beneath the moraine and that the unit reaches thicknesses of more than 50 m. In some holes, little or no indication is found of high velocities and Newmarket Till is either thin (e.g. borehole GSC-BH-MSR) or absent.

Spectral gamma-gamma logs — potential stratigraphic indicator?

The spectral gamma-gamma tool measures the number and energy level of gamma rays produced by the bombardment of the sediments by gamma rays from an active source (cobalt-60) in the tool. Gamma-ray interactions with soil include both photoelectric absorption at the low-energy end of the spectrum and Compton scattering effects in the higher energy range. Relative sediment density is inversely proportional to the observed gamma count rate due to Compton scattering (200–1000 keV determined from examination of the spectral distribution of energy). The relationship between density and count rate is nonlinear; in this paper, the relative density logs are shown as log (base 10) plots (Fig. 3a, 6).

In general, relative density logs correlate with the P-wave velocities. This is most noticeable for the 'very dense' and high-velocity gravel layer (40–55 m depth) in Figure 3a, but is also seen at a more subtle level in the lower part of the hole (e.g. below 140 m where both density and velocity increase in correlatable steps at 155, 175, and 186 m).

The Newmarket Till, however, does not seem to produce the same density/velocity correlation. Figure 6 shows that the density of the Newmarket Till is only slightly higher than that of the overlying Oak Ridges Moraine sediments, even though the unit is characterized by high P-wave velocities. This suggests that cementation may be an important factor contributing to the till's high seismic velocity.

The ratio of the high-energy/low-energy gamma counts ((200–1000 keV)/(50–150 keV)) is a measure of the average atomic number of the formation (again in relative terms; Killeen and Mwenifumbo, 1987). In Figure 6, Newmarket Till is clearly differentiated from overlying and underlying sediments by a higher spectral density ratio. An examination of the available logs suggests that spectral density ratios in the range of 3.0+ indicate higher heavy-mineral content and/or low porosity.

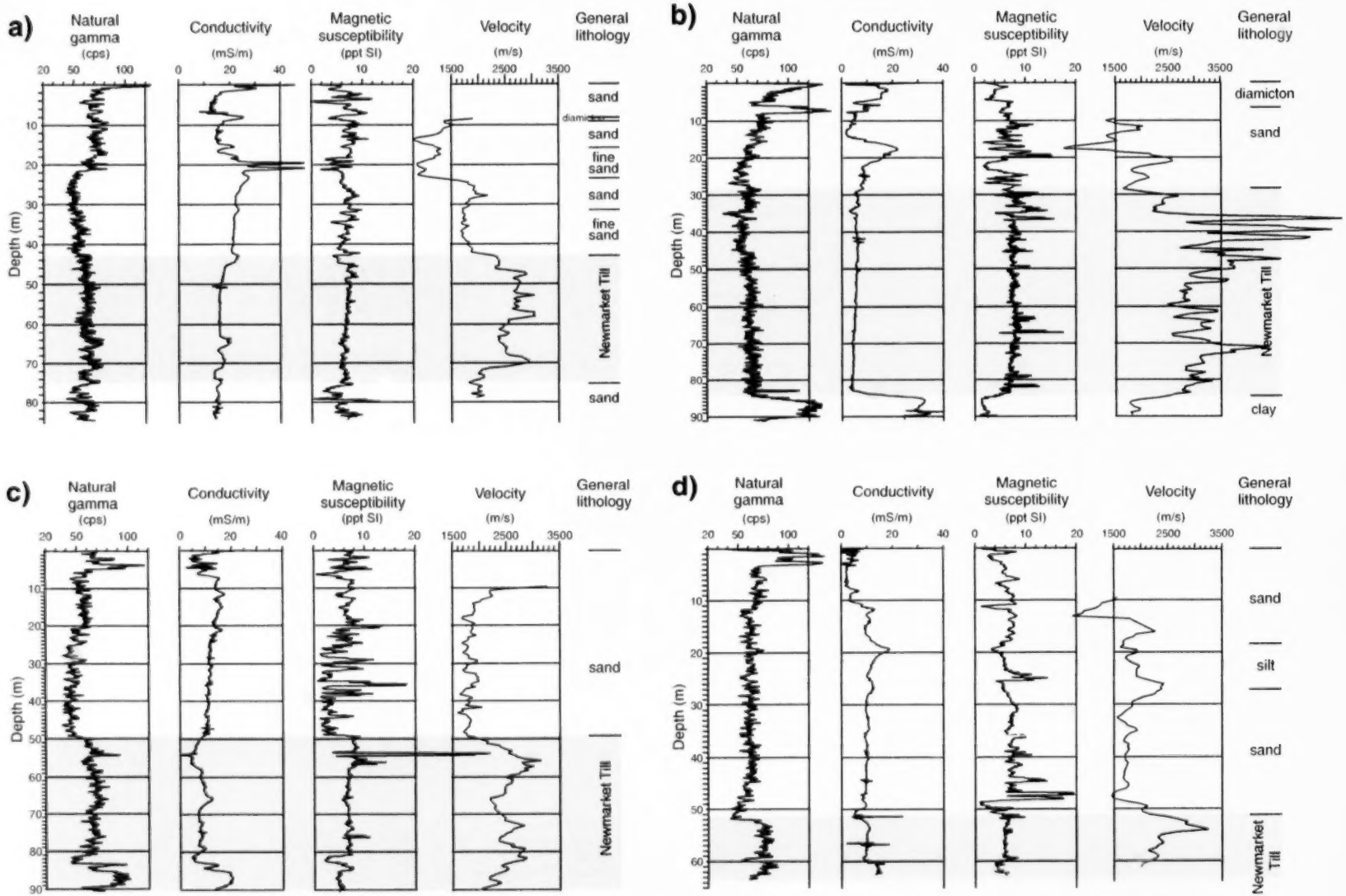

Figure 4. *Natural gamma, conductivity, magnetic susceptibility, and seismic velocity (P-wave) logs for boreholes* ***a****) OGS-PJB-15,* ***b****) OGS-PJB-19, c) OGS-PJB-17, and d) OGS-PJB-18.*

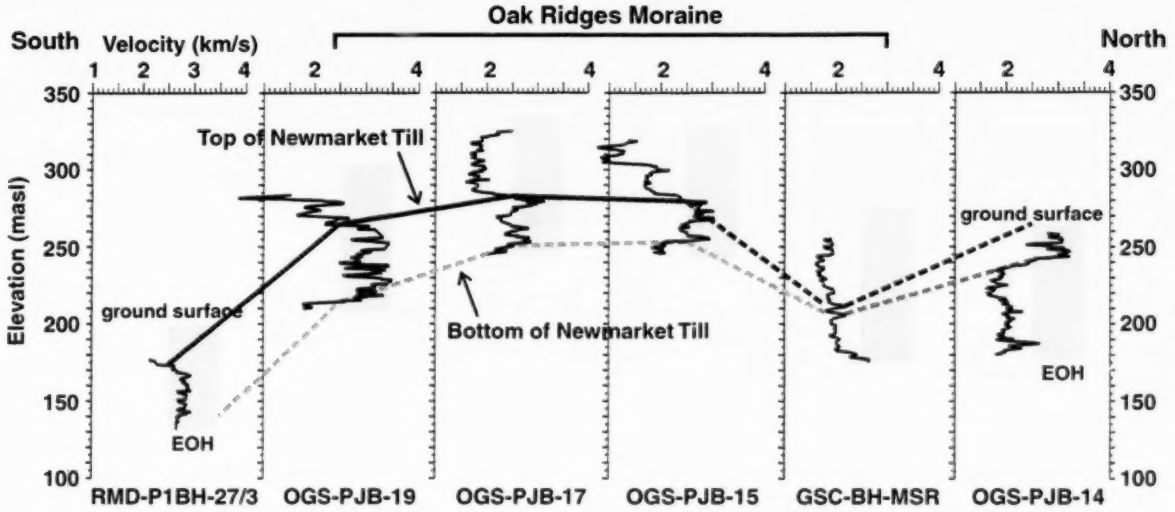

Figure 5. *Compressional velocity logs for a north-south borehole transect across the Oak Ridges Moraine (see Fig. 1) and the interpreted presence of Newmarket Till as indicated by high velocities (>2500 m/s). The shaded boxes indicate velocities between 2500 and 3500 m/s for elevations from the ground surface to the base of the borehole. Masl = metres above sea level; EOH = end of hole*

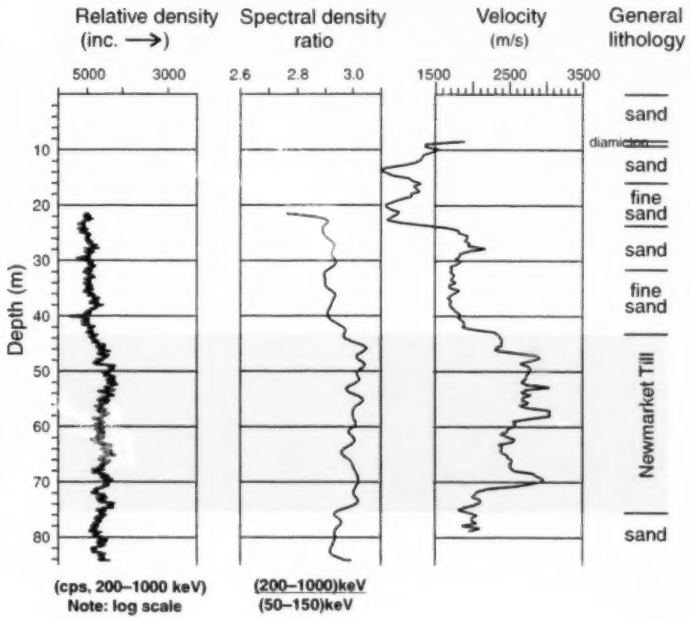

Figure 6.

Relative density, spectral density rates, and seismic velocity (P-wave) logs for borehole OGS-PJB-15.

To date, spectral gamma logs are available from only a limited number of stratigraphic boreholes in the Oak Ridges Moraine area, so the use of these logs for stratigraphic analysis is still under assessment. However, there are indications that the estimates of density and average atomic number may be useful as part of a suite of logs used for determining lithology and subsurface stratigraphy.

Derivation of porosity from downhole seismic logs

For hydrogeological purposes, it is desirable to attempt to relate geophysical parameters to hydrogeological properties. Corona and Mavko (1999) have examined the relationship between electrical conductivity and porosity in borehole GSC-BH-AUR. A preliminary attempt has also been made to consider the relationship between measured porosities and P- and S-wave velocities (Pullan et al., 2000).

Theoretically, P- and S-wave velocities are related to porosity, but in heterogeneous sediments, this relationship is complex, reflecting differences in the effective bulk and shear moduli with sediment type (e.g. Wyllie et al., 1956; Bachrach and Nur, 1998). Empirical relationships have long been used to estimate the porosity of reservoir rocks from P-wave velocities (e.g. Wyllie's (1963) time-average equation); such a relationship may also exist for unconsolidated sediments.

A clear correlation between porosity and seismic velocity can be seen from a compilation of data (Fig. 7) from borehole GSC-BH-AUR (Fig. 1) and in two deep boreholes in the Fraser River delta, British Columbia (Dallimore et al., 1995). These boreholes sample a wide range of Holocene and Pleistocene unconsolidated sediments (silts, sands, gravels, and tills). Figure 8 shows a comparison of porosities obtained from core measurements of weight per cent water with those derived from the velocity/porosity relationships (Fig. 7). The curves derived independently from P- and S-wave velocities are in general agreement within the fitted range of porosities ($0.25<N<0.55$), but do not agree well below 100 m depth, where the velocities are outside the range used to derive the porosity/velocity relationship.

This preliminary attempt to derive porosity from seismic velocity measurements suggests that further study of this relationship is warranted. The relationship requires better constraints from more detailed measurements, which will also allow an examination of the effect of varying lithological types, depth of burial, and consolidation factors (related to high velocities).

DISCUSSION

No single geophysical log can provide detailed lithological or stratigraphic assignment in the Oak Ridges Moraine area, but a combination of logs can be a powerful aid in making such assignments. Natural gamma logs, especially in combination with conductivity (or resistivity) and magnetic susceptibility logs, are an effective means of estimating lithological types, and when these logs are combined with seismic velocity information, the major stratigraphic units can usually be clearly identified. Table 2 provides a summary of measured downhole values in each of these units (it should be noted that 'lower deposits' in fact represent a combination of several units, which can only be subdivided once more data become available). For any given log, there are overlapping ranges of measured values between units; for combinations of logs, there are distinctive patterns associated with each major stratigraphic unit. As calibration of other logs with Oak Ridges Moraine stratigraphy improves, these additional logs could be used to better define the combination of geophysical properties that represents each unit.

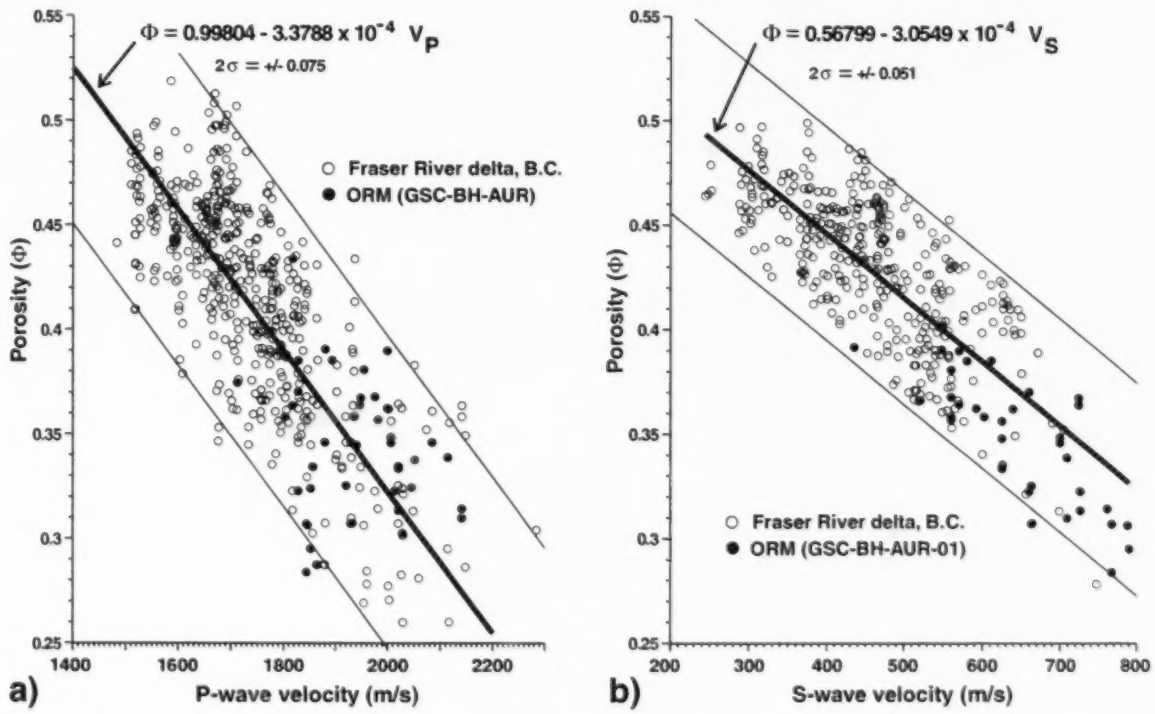

*Figure 7. Plots of measured sediment porosities versus **a**) compressional (P)-wave velocities (498 points) and **b**) shear (S)-wave velocities (387 points). These data come from the Fraser River delta, British Columbia (open circles) and from the Aurora borehole in the Oak Ridges Moraine (filled circles), and include measurements on a range of silts, sands, gravels, and tills. The heavy line indicates the best linear fit to the data and the lighter lines give the 2Φ (±95%) confidence limits.*

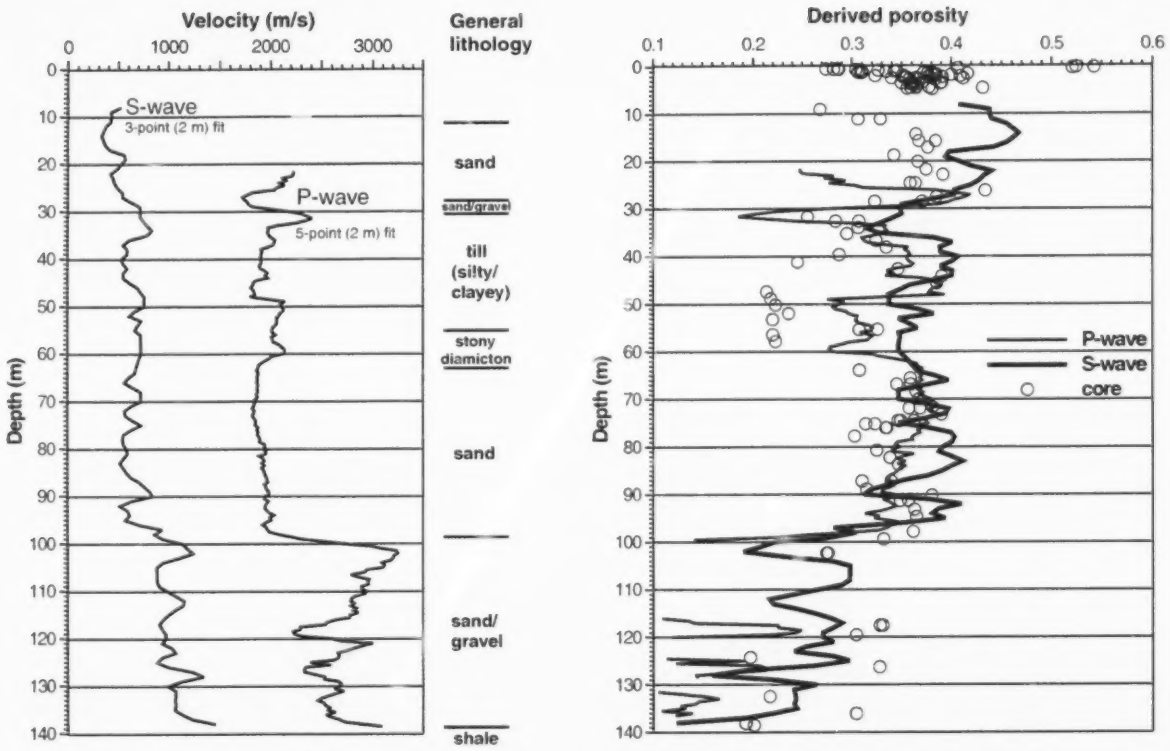

Figure 8. a) *Interval P- and S-wave velocities in borehole GSC-BH-AUR (see Fig. 1) determined from downhole seismic surveys.* ***b)*** *Plot of the measured porosities from core samples in this hole (open circles) and porosities derived from the velocity/porosity relationships shown in Figure 7.*

Table 2. Summary of measured values (natural gamma, conductivity, magnetic susceptibility, and P-wave velocity) for major stratigraphic units in the Oak Ridges Moraine area. The upper value is 'typical' for that unit; values in square brackets give the observed range.

Stratigraphic unit	Natural gamma (cps)*	Conductivity (mS/m)	Magnetic susceptibility (ppt SI)	P-wave velocity (m/s)	# boreholes encountering unit
Halton/Kettleby	[60–120]	[5–30]	[2–7]	—	3
ORM [silt/sand]	55–65 [40–90]	10–20 [2–42]	4–10 [2–20]	1700–1900 [1500–2400]	10
ORM [gravel]	40–50 [40–80]	[8–20]	[2–20]	2200 [1800–2400]	2
Newmarket Till	55–70 [40–90]	[4–22]	6–8 [4–12]	2600 [2000–3200]	5
Lower deposits	highly varied [40–140]	highly varied [5–75]	highly varied [2–20]	highly varied [1700–3000]	8

* Note that the count rate depends to some extent on the tool used.

The data presented here are limited to the logs that we were able to acquire, but it is important to note that other logging options should be investigated. Firstly, seismic velocity data could be acquired using a sonic tool instead of the surface-to-borehole techniques discussed here. This option would limit useable velocity information to sediments in which velocity exceeds the velocity of the borehole casing (~1900 m/s), but is a standard logging methodology that could be used specifically to identify the high velocities characteristic of the Newmarket Till. Secondly, porosity estimates could be obtained directly using a neutron logging tool, although this method requires a high-strength radioactive source.

Logging in steel-cased boreholes would present additional challenges. Several of the logs discussed here (conductivity, magnetic susceptibility, sonic) could not be acquired through steel casing, which also reduces the sensitivity of the radioactive tools. Downhole seismic logs can be acquired in a steel-cased hole, with a somewhat decreased signal-to-noise ratio.

SUMMARY

Downhole geophysical logs (natural gamma, conductivity, magnetic susceptibility, spectral gamma, temperature, and seismic velocity) have been acquired in 11 deep (~90–190 m), plastic-cased, continuously logged boreholes in the Oak Ridges Moraine area as part of a regional hydrogeological study. The downhole logs provide detailed physical properties (at submetre to metre scale) that aid in lithological characterization and in determining subsurface stratigraphy.

Natural gamma, conductivity, and magnetic susceptibility logs (especially when used in combination) have proven to be very useful in identifying lithological types downhole. The logs provide an estimate of grain size and allow the identification of geophysical signatures that can be used for hole-to-hole or regional correlations. For example, a distinct set of coarsening-upward units observed in the lower deposits in the westernmost borehole (Fig. 3a) can be correlated across a number of boreholes in the northwestern part of the study area, but has not yet been observed to the east. Such regional correlations (or variations) may provide a basis for the formulation of depositional models for the area.

However, it has been shown that major stratigraphic units in the Oak Ridges Moraine area are not always lithologically distinct. Natural gamma, conductivity, and magnetic susceptibility logs cannot be used alone to identify the Newmarket Till (a regionally significant aquitard). The Newmarket Till is a sandy till that behaves as an overconsolidated aquitard, apparently because of cementation. It is characterized by seismic velocities (>2500 m/s) that are significantly higher than those of most other sediments encountered in these boreholes. Thus, it is concluded that seismic velocities give a clearer indication of this stratigraphic unit than other geophysical logs when no continuous sediment core is available.

To date, the combination of natural gamma, conductivity, magnetic susceptibility, and seismic velocity logs constitutes the minimum suite of geophysical logs required to provide detailed lithology and stratigraphic assignment in the Oak Ridges Moraine area. Ongoing research includes an evaluation of the use of density estimates from geophysical logs (spectral gamma or neutron) to help define downhole lithology or stratigraphy, and an investigation of seismic velocities as an indicator of porosity.

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REFERENCES

Bachrach, R. and Nur, A.
1998: High-resolution shallow-seismic experiments in sand. Part II: Velocities in shallow unconsolidated sand: Geophysics, v. 63, p. 1234–1240.

Barnett, P.J.
1993: Geological investigations in the Oak Ridges Moraine area, parts of Scugog, Manvers, and Newcastle Township municipalities and Oshawa Municipality, Ontario; *in* Summary of Field Work and Other Activities 1993; Ontario Geological Survey, Miscellaneous Paper 162, p. 158–159.

1995: Quaternary geology of the Oak Ridges Moraine area, parts of Peterborough and Victoria counties and Durham and York Regional municipalities, Ontario; *in* Summary of Field Work and Other Activities 1995; Ontario Geological Survey, Miscellaneous Paper 164, p. 177–182.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F., and Pugin, A.
1998: On the origin of the Oak Ridges Moraine: Canadian Journal of Earth Sciences, v. 35, p. 1152–1167.

Boyce, J.I., Eyles, N., and Pugin, A.
1995: Seismic reflection, borehole, and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario: Canadian Journal of Earth Sciences, v. 32, p. 1331–1349.

Corona, W.W. and Mavko, G.
1999: Predicting clay content and porosity from gamma-ray and conductivity logs; *in* Proceedings, SAGEEP'99, Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 14–18, 1999, Oakland, California, p. 425–433.

Dallimore, S.R., Edwardson, K.A., Hunter, J.A., Clague, J.J., and Luternauer, J.L.
1995: Composite geotechnical logs for two deep boreholes in the Fraser River delta, British Columbia; Geological Survey of Canada, Open File 3018, 3 sheets.

Desbarats, A.J., Hinton, M.J., Logan, C.E., and Sharpe, D.R.
2001: Geostatistical mapping of leakance in a regional aquitard, Oak Ridges Moraine area, Ontario, Canada; Hydrogeology Journal, v. 9, p. 79–96.

Douma, M., Hunter, J.A., and Good, R.L.
1999: Borehole geophysical logging; Chapter 4 *in* A Handbook of Geophysical Techniques for Geomorphic and Environmental Research, (ed.) R. Gilbert; Geological Survey of Canada, Open File 3731, p. 57–67.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F., and Eyles, C.H.
1985: The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario Basin, Canada; Geoscience Canada, v. 12, p. 22–32.

Fligg, K. and Rodrigues, B.
1983: Geophysical well log correlations between Barrie and the Oak Ridges Moraine; Water Resources Branch, Ontario Ministry of the Environment, Map 2273.

Gerber, R.E. and Howard, K.
2000: Recharge through a regional till aquitard: three-dimensional flow model water balance approach; Ground Water, v. 38, p. 410–422.

Gwyn, Q.H.J. and Cowan, W.R.
1978: The origin of the Oak Ridges and Orangeville moraines of southern Ontario; Canadian Geographer, v. XXII, no. 4, p. 345–351.

Hinton, M.J., Russell, H.A.J., Bowen, G.S., and Ahad, J.M.E.
1998: Groundwater discharge in the Humber River watershed; *in* Proceedings, Groundwater in a Watershed Context Symposium; Canada Centre for Inland Waters, Burlington, Ontario, Canada, December 2–4, 1998; Canadian Water Resources Association, Cambridge, Ontario, p. 213–220.

Hunter, J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov, A., and Goriainov, N.N.
1998: Downhole seismic logging for high resolution reflection surveying in unconsolidated overburden; Geophysics, v. 63, p. 1371–1384.

Keys, W.S.
1989: Borehole Geophysics Applied to Ground-water Investigations; National Ground Water Association, Dublin, Ohio, 313 p.

Killeen, P.G. and Mwenifumbo, C.J.
1987: Interpretation of new generation geophysical logging in Canadian mineral exploration; *in* Proceedings, Second International Symposium on Borehole Geophysics for Minerals, Geotechnical, and Groundwater Applications, October 6–8, 1987, Golden, Colorado, p. 167–178.

McNeill, J.D., Hunter, J.A., and Bosnar, M.
1996: Application of a borehole induction magnetic susceptibility logger to shallow lithological mapping; Journal of Environmental and Engineering Geophysics, v. 0, p. 77–90.

Morin, R.H.
2000: Geophysical logging techniques used in the hydrogeologic characterization of sedimentary basins; *in* Proceedings, First Joint IAH-CNC and CGS Groundwater Specialty Conference (53rd Canadian Geotechnical Conference), October 15–18, 2000, Montreal, Quebec, p. 353–358.

Paillet, F.L.
1995: Integrating surface geophysics, well logs and hydraulic test data in characterization of heterogeneous aquifers; Journal of Environmental and Engineering Geophysics, v. 0, p. 1–13.

Pugin, A., Pullan, S.E., and Sharpe, D.R.
1999: Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario; Canadian Journal of Earth Sciences, v. 36, p. 409–432.

Pullan S.E., Hunter, J.A. Pugin, A., Burns, R.A., and Hinton, M.J.
2000: Downhole seismic logging techniques in a regional hydrogeology study, Oak Ridges Moraine, southern Ontario; *in* Proceedings, SAGEEP'2000, Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20–24, Arlington, Virginia, p. 643–652.

Pullan S.E., Pugin, A., Dyke, L.D. Hunter, J.A., Pilon, J.A., Todd, B.J., Allen, V.S., and Barnett, P.J.
1994: Shallow geophysics in a hydrogeological investigation of the Oak Ridges Moraine, Ontario; *in* Proceedings, SAGEEP'94, Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 27–31, Boston, Massachusetts, v. 1, p. 143–161.

Pullan, S.E., Pugin, A., Hunter, J.A., Robinson, S.D., Annecchione, M.A., and Leblanc, G.E.
2001: Applications of shallow geophysics in a regional geological and hydrogeological investigation, Oak Ridges Moraine, southern Ontario; *in* Proceedings, SAGEEP'2001, Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 4–7, Denver, Colorado, 17 pages (CD-ROM).

Sharpe, D.R., Barnett, P.J., Dyke, L.D., Howard, K.W.F., Hunter, G.T., Gerber, R.E., Paterson, J., and Pullan, S.E.
1994: Quaternary geology and hydrogeology of the Oak Ridges Moraine area; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Waterloo, 1994, Field Trip A7, Guidebook, 32 p.

Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J., and Pugin, A.
1996: Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geologic models; *in* Current Research 1996-E; Geological Survey of Canada, p. 181–190.

Sharpe, D.R, Hinton, M.J., Russell, H.A.J., and A.J. Desbarats,
2002: The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, southern Ontario; Geoscience Canada, v. 29, no. 1, p. 3–20.

Sibul, U., Wang, K. T., and Vallery, D.
1977: Ground-water resources of the Duffins Creek–Rouge River drainage basins; Ontario Ministry of the Environment, Water Resources Branch, Water Resources Report 9, 109 p.

Taylor, A., Allen, V., Burgess, M., and Naufal, J.
1999: Wellbore temperature measurements and preliminary interpretation in terms of groundwater movement in the Oak Ridges Moraine, Ontario; Geological Survey of Canada, Open File 3787, 130 p.

Wyllie, M.R.J.
1963: The Fundamentals of Well Log Interpretations; Academic Press, New York, 238 p.

Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W.
1956: Elastic wave velocities in heterogeneous porous media; Geophysics, v. 1, p. 41–70.

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